

# Lifetime Improvement in Wireless Sensor Networks via Collaborative Beamforming and Cooperative Transmission

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## Abstract

Collaborative beamforming (CB) and cooperative transmission (CT) have recently emerged as communication techniques that can make effective use of collaborative/cooperative nodes to create a virtual multiple-input/multiple-output (MIMO) system. Extending the lifetime of networks composed of battery-operated nodes is a key issue in the design and operation of wireless sensor networks. This paper considers the effects on network lifetime of allowing closely located nodes to use CB/CT to reduce the load or even to avoid packet-forwarding requests to nodes that have critical battery life. First, the effectiveness of CB/CT in improving the signal strength at a faraway destination using energy in nearby nodes is studied. Then, the performance improvement obtained by this technique is analyzed for a special 2D disk case. Further, for general networks in which information-generation rates are fixed, a new routing problem is formulated as a linear programming problem, while for other general networks, the cost for routing is dynamically adjusted according to the amount of energy remaining and the effectiveness of CB/CT. From the analysis and the simulation results, it is seen that the proposed method can reduce the payloads of energy-depleting nodes by about 90% in the special case network considered and improve the lifetimes of general networks by about 10%, compared with existing techniques.

## I. INTRODUCTION

In wireless sensor networks [1], extending the lifetimes of battery-operated devices is considered a key design issue that increases the capability of uninterrupted information exchange and alleviates the burden of replenishing batteries. A survey of energy constraints for sensor networks is presented in [2]. In the literature of sensor networks, there are many lifetime definitions: the time until the first node failure [3], [4], [5]; the time at which only a certain fraction of nodes survives [2] [6]; the time until the first loss of coverage [7]; mean expiration time [8]; and lifetime in terms of alive flows [9] and packet delivery rates [10].

To improve network lifetimes, many approaches have been proposed. In [4], a data routing algorithm has been proposed with an aim to maximize the minimum lifetime over all nodes in wireless sensor networks. Upper bounds on lifetime have been derived in [7] using an energy-efficient tree with static and dynamic optimization. In [11], the network lifetime has been maximized by employing an accumulative broadcast strategy. The work in [12] has considered provisioning additional energy on existing nodes and deploying relays to extend the lifetime.

Recently, collaborative beamforming (CB) [13] and cooperative transmission (CT) [14] [15] have been proposed as new communication techniques that fully utilize spatial diversity and multiuser diversity. The basic idea is to allow nodes in the network to help transmit/relay information for each other, so that collaborative/cooperative nodes create a virtual multiple-input/multiple-output (MIMO) system. Most existing works on CB/CT concentrate on how to improve performance at the physical layer. Recently, some works have also studied the impacts of CB/CT on the design of higher layer protocols. In [16] [17] [18], the authors have investigated the choice of appropriate nodes for cooperation and how much cooperation should be facilitated. A game theoretic approach for relay selection has been proposed in [19]. In [20], cooperative routing protocols have been constructed based on non-cooperative routes.

In this paper, we investigate new routing protocols to improve lifetimes of wireless sensor networks using CB/CT communication techniques. First, we study the fact that CB/CT can effectively increase the signal strength at the destination, which in turn can increase the transmission range. We obtain a closed-

form analysis of the effectiveness of CT similar to that of CB in [13]. Then, we formulate the problem so as to maximize the network lifetime defined as the time at which the first node fails. The *new idea* is that closely located nodes can use CB/CT to reduce the loads or even avoid packet forwarding requests to nodes with critical battery lives. From the analysis of a 2D disk case using CB/CT, we investigate how to bypass the energy-depleting nodes. Then we propose two algorithms for general networks. If the information-generation rates are fixed, we can formulate the problem as a linear programming problem. Otherwise, we propose a heuristic algorithm to dynamically update the cost for routing tables according to the remaining energy and willingness for collaboration. From the analysis and simulation results, we see that the proposed new routing schemes can reduce the payloads of the energy-depleting nodes by about 90% in the 2D disk network compared to the pure packet-forwarding scheme, and can improve the lifetimes of general networks by about 10%, compared to the schemes in [4].

This paper is organized as follows: In Section II, we describe the system model and study the ability to enhance the destination signal strength by CB/CT. In Section III, we formulate the lifetime maximization problem, analyze a 2D disk case, and propose algorithms for general networks. Simulation results are given in Section IV and conclusions are drawn in Section V.

## II. SYSTEM MODEL AND EFFECTIVENESS OF CB/CT

We consider a wireless network where each sensor node is equipped with a single ideal isotropic antenna. There is no power control for each node; i.e., the node transmits with power either  $P$  or 0. We assume sufficiently separated nodes so that any mutual coupling effects among the antennas of different nodes are negligible. For CB, there is no reflection or scattering of the signal. Thus, there is no multipath fading or shadowing. For CT, we assume Rayleigh fading.

For traditional direct transmission, if a node tries to reach another node at a distance of  $A$ , the signal to noise ratio (SNR) is given by

$$\Gamma = \frac{PC_0A^{-\alpha}|h|^2}{\sigma^2}, \quad (1)$$

where  $C_0$  is a constant,  $\alpha$  is the propagation loss factor,  $h$  is the channel fading gain, and  $\sigma^2$  is the

thermal noise level. Here,  $C_0$  includes other effects such as the antenna gains and is assumed to be unity without loss of generality. We define the energy cost of such a transmission for each packet as one unit. We further define  $A_0$  to be the maximal distance over which a minimal link quality  $\gamma_0$  can be maintained, i.e.  $\Gamma(A_0) = \gamma_0$ .

In Figure 1, we show the system model with CB/CT. In traditional sensor networks, the only choice a node has is to forward packets toward the sink which serves as a data gathering point. This packet forwarding will deplete the energy of the nodes near the sink, since they have to transmit a lot of other nodes' packets. To overcome the above problem, we propose another choice for a node by forming CB/CT with the nearby nodes so as to transmit further towards the sink. By using the nearby nodes as virtual antennas of a MIMO system, we can leverage the energy usage of the nodes having different locations and different remaining energies. As a result, the network lifetime can be improved. In the rest of this section, we study how CB and CT can improve link quality. Notice that CB and CT technologies are investigated independently in the rest of this paper for lifetime improvement over wireless sensor networks.

#### A. Effectiveness of Collaborative Beamforming

We assume sensor nodes are uniformly distributed with a density of  $\rho$ . If there are a total of  $N$  nodes for collaborative beamforming within a disk with radius  $R$ . We have

$$N = \lfloor \rho \pi R^2 \rfloor. \quad (2)$$

Each node has polar coordinate  $(r_k, \psi_k)$  with the origin at the disk center. The distance from the center to the beamforming destination is  $A$ . The Euclidean distance between the  $k^{th}$  node and the beamforming destination can be written as:

$$d_k = \sqrt{A^2 + r_k^2 - 2r_k A \cos(\phi - \psi_k)}, \quad (3)$$

where  $\phi$  denotes azimuthal direction and is assumed to be a constant. By using loop control or the Global Positioning System, the initial phase of node  $k$  can be set to

$$\psi_k = -\frac{2\pi}{\lambda} d_k(\phi), \quad (4)$$

where  $\lambda$  is the wavelength of the radio frequency carrier.

Define  $\mathbf{z} = [z_1 \dots z_N]^T$  with

$$z_k = \frac{r_k}{R} \sin(\psi_k - \phi/2). \quad (5)$$

The array factor of CB can be written as

$$F(\phi|\mathbf{z}) = \frac{1}{N} \sum_{k=1}^N e^{-j4\pi R \sin(\frac{\phi}{2}) z_k / \lambda}. \quad (6)$$

The far-field beam pattern can be defined as:

$$P(\phi|\mathbf{z}) = |F(\phi|\mathbf{z})|^2 = \frac{1}{N} + \frac{1}{N^2} \sum_{k=1}^N e^{-ja(\phi)z_k} \sum_{l \neq k} e^{ja(\phi)z_l}, \quad (7)$$

where

$$a(\phi) = \frac{4\pi R \sin \frac{\phi}{2}}{\lambda}. \quad (8)$$

Define the directional gain  $D_{av}^{CB}$  as the ratio of radiated concentrated energy in the desired direction over that of a single isotropic antenna. From Theorem 1 in [13], for large  $\frac{R}{\lambda}$  and  $N$ , the following lower bound for far-field beamforming is tightly held:

$$\frac{D_{av}^{CB}}{N} \geq \frac{1}{1 + \mu \frac{N\lambda}{R}}, \quad (9)$$

where  $\mu \approx 0.09332$ .

Considering this directional gain, we can improve the direct transmission by a factor of  $D_{av}^{CB}$ . Consequently, the transmission distance is improved. Notice that this transmission distance gain for one transmission is obtained at the expense of consuming a total energy of  $N$  units from the nearby nodes.

### B. Effectiveness of Cooperative Transmission

In this subsection, we discuss another technique for improving the link quality. Similar to the CB case, we assume  $N$  nodes are uniformly distributed over a disk of radius  $R$ . The probability density function of the node's distance  $r$  from the center of the disk is given by

$$q(r) = \frac{2r}{NR^2}, \quad 0 \leq r \leq R, \quad (10)$$

and the node's angular coordinate  $\psi$  is uniformly distributed on  $[0, 2\pi)$ .

Suppose at stage 1, node 1 transmits to the next hop or sink which is called the destination. The received signals at node 2 through node  $N$  at stage 1 can be expressed as:

$$z_k = \sqrt{Pr_k^{-\alpha}} h_k^r x + n_k^r, \quad k = 2, \dots, N, \quad (11)$$

and the received signal at the sink at stage 1 is given by

$$y_1 = \sqrt{Pd_1^{-\alpha}} h_1 x + n_1. \quad (12)$$

Then in the following stages, node 2 through node  $N$  relay node 1's information if they decode it correctly. The received signals at the destination in the subsequent stages are

$$y_k = \sqrt{Pd_k^{-\alpha}} h_k x + n_k, \quad k = 2, \dots, N. \quad (13)$$

In the rest of this subsection, we call node 1 the source and nodes 2 through  $N$  the relays. Here,  $P$  is the transmitted power.  $h_k^r$  and  $h_k$  are the channel fading gains of source-relay and relay-destination, respectively. The channel fading gains are modeled as independent, circularly-symmetric, complex, Gaussian random variables with zero mean and unit variance.  $x$  is the transmitted data symbol having unit energy.  $n_k$  and  $n_k^r$  are independent thermal noises at the destination and relay for node  $k$ , respectively. Without loss of generality, we assume that all noises have variance  $\sigma^2$ .

*Theorem 1:* Define  $D_{av}^{CT}$  to be the number of times a link can be enhanced at the destination using CT. Under the far-field condition and the assumption that channel links between the source and the relays are sufficiently good, we have the following approximation:

$$\frac{D_{av}^{CT}}{N} \approx \frac{1 + (N-1) {}_2F_1\left(\frac{2}{\alpha}, -L; \frac{\alpha+2}{\alpha}; \frac{\sigma^2 R^\alpha}{4P}\right)}{N}, \quad (14)$$

where  $L$  is the frame length and  ${}_2F_1$  is the hypergeometric function

$${}_2F_1(a, b; c; z) = \sum_{n=0}^{\infty} \frac{(a)_n (b)_n}{(c)_n} \frac{z^n}{n!}, \quad (15)$$

and where  $(a)_n$  is the Pochhammer symbol defined as

$$(a)_n = a(a+1) \cdots (a+n-1).$$

The calculation of hypergeometric functions is discussed in [23].

*Proof:* The received SNR at the  $k^{th}$  node at stage 1 can be written as

$$\Gamma_k = \frac{PC_0 r_k^{-\alpha} |h_k^r|^2}{\sigma^2}, \quad (16)$$

where  $|h_k^r|^2$  is the square magnitude of the channel fade and follows an exponential distribution with unit mean.

Without loss of generality, we assume BPSK modulation is used and  $C_0 = 1$ . The probability of successful transmission of a packet of length  $L$  is given by

$$P_r^k(r_k) = \left( \frac{1}{2} + \frac{1}{2} \sqrt{\frac{P}{P + \sigma^2 r_k^\alpha}} \right)^L. \quad (17)$$

For fixed  $(r_k, \psi_k)$ , the average power that arrives at the destination can be written as

$$D^{CT} = \sum_{k=1}^N P d_k^{-\alpha} P_r^k. \quad (18)$$

For node 1,  $r_1 = 0$ . We can write the average gain in link quality in the following generalized form:

$$D_{av}^{CT} = \sum_{k=1}^N \int_0^R \int_0^{2\pi} \frac{A^\alpha}{2\pi} d_k^{-\alpha} P_r^k(r_k) q(r_k) dr_k d\psi_k. \quad (19)$$

Since each node is independent of the others, we omit the designator  $k$  and rewrite (19) as

$$D_{av}^{CT} = 1 + (N-1) \int_0^{2\pi} \int_0^R \frac{r}{\pi A^{-\alpha} R^2} (A^2 + r^2 - 2rA \cos \psi)^{-\frac{\alpha}{2}} P_r(r) dr d\psi, \quad (20)$$

where the 1 on the right-hand side (RHS) is obtained because the first node's location is at  $r_1 = 0$ . With the far field assumption, we have

$$\frac{1}{2\pi} \int_0^{2\pi} (A^2 + r^2 - 2rA \cos \psi)^{-\frac{\alpha}{2}} d\psi \approx A^{-\alpha}. \quad (21)$$

The average link quality gain is approximated by

$$D_{av}^{CT} \approx 1 + (N-1) \frac{2}{R^2} \int_0^R r P_r(r) dr. \quad (22)$$

With the assumption of sufficiently good channels between the source and the relays, using a Taylor expansion, we have the following approximation of (17):

$$P_r(r) \approx \left( 1 - \frac{\sigma^2 r^\alpha}{4P} \right)^L. \quad (23)$$

Since

$$\int_0^R r \left(1 - \frac{\sigma^2 r^\alpha}{4P}\right)^L dr = \frac{1}{2} R^2 {}_2F_1\left(\frac{2}{\alpha}, -L; \frac{\alpha+2}{\alpha}; \frac{\sigma^2 R^\alpha}{4P}\right), \quad (24)$$

we obtain (14). ■

In Figure 2, we compare the numerical and analytical results of  $D_{av}$  for different radii  $R$ . Here  $A = 1000\text{m}$ ,  $P = 10\text{dbm}$ ,  $\sigma^2 = -70\text{dbm}$ ,  $\alpha = 4$ ,  $L = 100$ , and  $N = 10$ . When  $R$  is sufficiently small; i.e., when the cooperative nodes are close to each other, the average link gain over the number of cooperative nodes is almost one. When  $R$  increases, the efficiency of transmission to a faraway destination decreases because the links from the source to the relays degrade. We can see that the numerical results fit the analysis very well, which suggests that the approximation in (14) is a good one.

### III. CB/CT LIFETIME MAXIMIZATION

In this section, we first define the lifetime of sensor networks and formulate the corresponding optimization problem. Then, using a 2D disk case, we demonstrate the effectiveness of lifetime improvement analytically using CB/CT. Finally, two algorithms are proposed for general network configurations with fixed and dynamic information rates, respectively.

#### A. Problem Formulation

In Figure 3, we show the routing model with CB/CT. A wireless sensor network can be modeled as a directed graph  $G(M, \mathbb{A})$ , where  $M$  is the set of all nodes and  $\mathbb{A}$  is the set of all links  $(i, j)$ ,  $i, j \in M$ . Here the link can be either a direct transmission link or a link with CB/CT. Let  $S_i$  denote the set of nodes that the  $i^{th}$  node can reach using direct transmission. Denote by  $C_i^m$  the set of nodes that node  $i$  needs to use CB/CT with in order to reach node  $m$ . In the example in Figure 3,  $C_i^m = \{l\}$  and  $C_i^k = \{\}$ . A set of origin nodes  $O$  where information is generated at node  $i$  with rate  $Q_i$  can be written as

$$O = \{i | Q_i > 0, i \in M\}. \quad (25)$$

A set of destination nodes is defined as  $D$  where

$$D = \{i | Q_i < 0, i \in M\}. \quad (26)$$



Here the sign of  $Q_i$  represents the direction of flow.

Let  $\mathbf{q} = \{q_{ij}\}$  represent the routing and the transmission rates. In this paper, we use the lifetime until the first node failure as an example. Other definitions of lifetime can be treated similarly. Suppose node  $i$  has remaining energy  $E_i$ . Then, the lifetime for node  $i$  can be written as:

$$T_i(\mathbf{q}) = \frac{E_i}{\sum_{j \in S_i} q_{ij} + \sum_{i \in C_j^m, \forall j, m} q_{jm}}, \quad (27)$$

where the first term in the denominator is for direct transmission and the second term in the denominator is for CB/CT. Notice that  $C_j^m$  is not a function of  $\mathbf{q}$ , so that we can formulate the lifetime maximization problem as

$$\begin{aligned} & \max_{\mathbf{q}} \min T_i \\ \text{s.t. } & \begin{cases} q_{ij} \geq 0, \forall i, j, \\ \sum_{j, i \in S_j} q_{ij} + Q_i = \sum_{k \in S_i} q_{ik}, \end{cases} \end{aligned} \quad (28)$$

where the second constraint is for flow conservation. Notice that there are two differences between (28) and lifetime maximization in traditional sensor networks without CB/CT. First, in addition to packet forwarding, the nodes in (28) need to spend additional energy to form CB/CT with other nodes. Second, there are more available routes for nodes in the formation of (28) than those in the formulation without CB/CT.

### B. 2D Disk Case Analysis

In this subsection, we study a network confined to a 2D disk. Nodes with equal energy remaining are uniformly located within a circle of radius  $B_0$ . One sink is located at the center of the disk  $(0,0)$ . Each node has a unit amount of information to transmit. Here we assume the node density is large enough, so that each node can find enough nearby nodes to form CB/CT to reach the faraway destination.

First, we consider the traditional packet-forwarding scheme without CB/CT. Suppose the node density is  $\rho$ . The number of nodes at approximate distance  $B$  to the sink is  $\rho 2\pi B \Delta B$ , where  $\Delta B$  denotes the degree of approximation. Recall that  $A_0$  is the maximal distance for direct transmission. The nodes located at distance  $B + A_0$  transmit to the nodes at distance  $B$ , and there are  $\rho 2\pi (B + A_0) \Delta B$  such

nodes. We assume a unit information-generation rate for each node. The number of packets needing transmission for each node at distance  $B$  to the sink is given by

$$N_{pf}(B) = \sum_{n=0}^{\lfloor \frac{B_0-B}{A_0} \rfloor} \left( 1 + \frac{nA_0}{B} \right). \quad (29)$$

Notice that the burden of forwarding data increases when the nodes are close to the sink.

If all nodes use their neighbor nodes to communicate with the sink directly, we call this scheme pure CB/CT. To achieve the range of  $B$ , we need  $N_{CB/CT}(B)$  nodes for CB/CT so that a direct link to the sink can be established; i.e.,

$$D_{av}^{CB/CT}(N_{CB/CT}(B)) = \left( \max\left(\frac{B}{A_0}, 1\right) \right)^\alpha. \quad (30)$$

For collaborative beamforming, we can calculate

$$N_{CB}(B) \geq \frac{1}{2} \left( c_0(2 + c_0c_1^2) + c_0^{1.5}c_1\sqrt{4 + c_0c_1^2} \right) \quad (31)$$

where  $c_0 = (\max(\frac{B}{A_0}, 1))^\alpha$  and  $c_1 = \mu\lambda\sqrt{\rho\pi}$ . For cooperative transmission, numerical results need to be used to obtain the inverse of  ${}_2F_1$  in Theorem 1.

In Figure 4, we show the average number of transmissions per node vs. disk size  $B_0$ . We can see that for traditional packet forwarding, the node closest to the sink has the most transmissions per node; i.e., it has the lowest lifetime if the initial energy is the same for all nodes. On the other hand, for the pure CB/CT scheme, more nodes need to transmit to reach the sink directly when  $B_0$  is larger. The transmission is less efficient than packet forwarding, since the propagation loss factor  $\alpha$  is larger than 1 in most scenarios. The above facts motivate the joint optimization case in which nodes transmit packets with different probabilities to emulate traditional packet forwarding and CB/CT.

As we have stated, if the faraway nodes can form CB/CT to transmit directly to the sink and bypass these energy-depleting nodes, the overall network lifetime can be improved. Notice that in this special case, if the faraway nodes form CB/CT to transmit to nodes other than the sink, the lifetime will not be improved. For each node with distance  $B$  to the sink, we have the probability  $P_r(B)$  of using CB/CT as

TABLE I  
PAYLOAD REDUCTION VS. DISK SIZE

$B_0$	2	4	6	8	10
$N_{joint}(B)$	2.8	10.3	23.4	42.5	64.5
$N_{pf}(B)$	52	153	256	358	460
Saving %	94.6	93.3	90.9	88.1	86.0

$$N_{joint}(B) = [1 - P_r(B) + N_{CB/CT}(B)P_r(B)] \left\{ \sum_{n=0}^{\lfloor \frac{B_0-B}{A_0} \rfloor} \left(1 + \frac{nA_0}{B}\right) \Pi_{j=1}^n [1 - P_r(B + jA_0)] \right\}, \quad (32)$$

where the first term on the RHS is the necessary transmitting energy per packet, and the second term is the total number of transmitting packets. The goal is to adjust  $P_r(B)$  such that the heaviest payload is minimized; i.e.,

$$\min_{1 \geq P_r(B) \geq 0} \max N_{joint}(B). \quad (33)$$

If  $P_r(B) = 0, \forall B$  the scheme is traditional packet forwarding, and if  $P_r(B) = 1, \forall B > A_0$  the scheme is pure CB/CT.

Notice that  $N_{joint} \geq 1$ , and in (32) the second term on the RHS depends on the probabilities of CB/CT being larger than  $B$ . Therefore, we can develop an efficient bisection search method to calculate (33). We define a temperature  $\kappa$  that is assumed to be equal to or greater than  $N_{joint}(B), \forall B$ . We can first calculate  $P_r(B_0)$  at the boundary of the network where  $N_{joint}(B_0) = \kappa$  and the second term on the RHS of (32) is one. Then, we can derive all  $N_{joint}(B)$  and  $P_r(B)$  by successively reducing  $B$ . If  $\kappa$  is too large, most information is transmitted by CB/CT, and the nodes faraway from the sink waste too much energy for CB/CT. In this case, we can reduce  $\kappa$ . On the other hand, if  $\kappa$  is too small, the nodes close to the sink must forward too many packets and the resulting  $N_{joint}(B)$  is larger than  $\kappa$  when  $B$  is small. A bisection search method can find the optimal values of  $\kappa$ ,  $N_{joint}(B)$ , and  $P_r(B)$ .

In Figure 4, we show the joint optimization case where the node density is sufficiently large. We can see that to reduce the packet-forwarding burdens of the nodes near the sink, the faraway nodes form CB/CT

to transmit to the sink directly. The formulation of CB/CT will increase the number of transmissions per node for themselves, but reduce the number of transmissions per node for the nodes near the sink. By leveraging between the energy consumed for CB/CT and packet forwarding, the proposed scheme can reduce the payload burdens and consequently improve the network lifetime significantly. In Table I, we show the optimal  $N_{joint}(B)$ ,  $N_{pf}(B)$ , and the payload reductions for the proposed joint scheme over traditional packet forwarding. We can see that the payloads are reduced by about 90%. The performance improvement decreases when the size of the network increases. This is because CB/CT costs too much transmission energy to connect to the sink directly if the propagation loss is greater than 1.

### C. General Case Algorithms

In this section, we first consider the case in which the information-generation rates are fixed for all nodes and develop a linear programming method to calculate the routing table. Define  $\hat{q}_{ij} = Tq_{ij}$ , where  $T$  is the lifetime. If  $C_j^m, \forall j, m$  is known, the problem in (28) can be written as a linear programming problem:

$$\begin{aligned} & \max T \\ & \text{s.t.} \begin{cases} \hat{q}_{ij} \geq 0, \forall i, j; \\ (\sum_{j \in S_i} \hat{q}_{ij} + \sum_{i \in C_j^m, \forall j, m} \hat{q}_{jm}) \leq E_i, \forall i; \\ \sum_{j, i \in S_j} \hat{q}_{ji} + TQ_i = \sum_{k \in S_i} \hat{q}_{ik}, \forall i \in M - D, \end{cases} \end{aligned} \quad (34)$$

where the second constraint is the energy constraint and the third constraint is for flow conservation.

Notice that (34) has a linear objective function and can also be written in a max-min form.

In practice, it is difficult to find  $C_j^m$  since the complexity will increase exponentially with the number of potential collaborative/cooperative nodes in the set. One possible way to simplify the calculation of the set  $C_j^m$  is to select the nearest neighbor for CB/CT.  $C_j^m = 1$ , if node  $j$ 's nearest neighbor can help node  $j$  to reach node  $m$ . Obviously, this simplification is suboptimal for (34).

Next, if the information rate is random, each node dynamically updates its cost according to its remaining energy and with consideration of CB/CT. Some heuristic algorithms can be proposed to update the link cost dynamically. Here the initial energy is  $E_i$ . Denote the current remaining energy as  $\underline{E}_i$ . We define the cost for node  $i$  to communicate with node  $j$  as

$$\text{cost}_{ij} = \left( \frac{E_i}{\underline{E}_i} \right)^{\beta_1} + \sum_{l \in C_i^j} \left( \frac{E_l}{\underline{E}_l} \right)^{\beta_2}, \quad (35)$$

where  $\beta_1$  and  $\beta_2$  are positive constants. Their values affect the routing algorithms to allocate the packets between the energy-sufficient and energy-depleting nodes, and between the direct transmission and CB/CT. Notice that if  $\beta_2 = 0$  in (35), the cost function degrades to the normalized residual energy cost function in [4].

We assume that each node periodically broadcasts a HELLO packet to its neighbors to update the topology information. Therefore, the minimization problem in (28) can be solved by applying any distributed shortest path routing algorithm such as the Bellman-Ford algorithm [22]. There are two differences to the traditional shortest path problem. First, beyond direct transmission links, there are additional links constructed by CT/CB. Second, when CT/CB links are used, the energy is consumed not only in the transmission node but also in the collaborative/cooperative nodes.

#### IV. SIMULATION RESULTS

We assume the sensor nodes and one sink are randomly located within a square of size  $\mathbb{L} \times \mathbb{L}$ . Each node has power of 10dbm, and the noise level is -70dbm. The propagation loss factor is 4. The minimal link SNR  $\gamma_0$  is 10dB. The initial energy of all nodes is assumed to be unit and the average information rates for all nodes are 1.

In Figure 5, we show a snapshot of a network of 5 sensor nodes and a sink with  $\mathbb{L} = 50\text{m}$ . Here node 1 is the sink. The solid lines are the direct transmission links, and the dotted line from node 6 to the sink is the CB/CT link with the help of node 5. For the traditional packet-forwarding scheme, the best flow is

$$\hat{q}_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0.1 \\ 0 & 0.3 & 0 & 0 & 0 & 0 \\ 0 & 0.3 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (36)$$

with the energy consumed for all nodes given by  $[0, 1.0, 0.2, 0.2, 0.3, 0.3]$ . Because node 2 is the only node that can communicate with the sink, the best network lifetime is limited to 0.2 before node 2 runs out of battery.

With a new link from node 6 to node 1 with CB/CT, the best flow is

$$\hat{q}_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.321 & 0 & 0 & 0 & 0.012 \\ 0 & 0 & 0 & 0 & 0 & 0.333 \\ 0 & 0.23 & 0 & 0 & 0 & 0.103 \\ 0.667 & 0.115 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (37)$$

with the energy consumed for all nodes given by  $[0, 1.000, 0.333, 0.333, 1.0000, 0.782]$ . Here some flow can be sent to the sink via node 6 instead of node 2. Because of CB/CT, node 5 has to consume its own energy. The lifetime becomes 0.333 which is a 67% improvement over packet forwarding.

In Figure 6, we show the dynamic behavior for the algorithm using (35). Here  $\beta = \beta_1 = \beta_2 = 1$ . We show the remaining energy of node 2 and node 5 over time with and without CB/CT, respectively. We can see that without CB/CT, node 2 runs out of battery energy at time 0.2. Since node 2 is the only node that is able to connect to the sink, the whole network dies at time 0.2, even though node 5 still has more than 70% of its energy left. With CB/CT, node 5 can help the link from node 6 to the sink, so as to relieve the packet-forwarding burden of node 2. As a result, node 2 can extend its lifetime to 0.333. In this example, we show that the dynamic algorithm using (35) has the same performance as that of the linear programming solution using (34). If we increase  $\beta$ , the curves of node 2 and node 5 with CB/CT coincide with each other.

In Figure 7, we show the link cost changes over time. We can see that the cost for each link increases almost linearly with the increase of time or equivalently with the decrease of the remaining energy at the beginning. When the nodes' energy is critical, the price will increase quickly. The function in (35) can be viewed as a boundary function [21] for the constrained optimization problem. If the optimization is a minimization, the boundary function increases the objective function significantly when the constraints are not satisfied. Here the equivalent constraint is the non-negative remaining energy. Similar to the boundary function, the cost functions in (35) prevent the routing algorithm from using the energy-depleting nodes. For different values of  $\beta$ , the link costs have different sensitivities to remaining energy.

In Figure 8, we compare the performance of three algorithms: the shortest path, the algorithm in [4], and the proposed CB/CT algorithm. Here  $\mathbb{L} = 100\text{m}$ . As the number of nodes increases, the performance of the shortest path algorithm decreases. This decrease happens because more nodes need packet forwarding by the nodes near the sink. Consequently, the nodes near the sink die more quickly and the network lifetimes are thus shorter. Compared with the algorithm in [4], the proposed schemes have about 10% performance improvement. This improvement is achieved because of the alternative routes to the sink that can be established by CB/CT. With the increase in the number of nodes, the performance of the algorithm in [4] and the proposed algorithm can be slightly improved, because there are more choices for the sensor nodes to connect to the sink.

In Figure 9, we show the lifetime improvement over the pure packet-forwarding scheme as a ratio of  $\beta_2/\beta_1$  for  $\beta_1 = 0.1, 1$ , and  $10$ , respectively. Recall that  $\beta_1$  and  $\beta_2$  represent the willingness of the nodes to participate in packet forwarding or in CB/CT. When  $\beta_2 < \beta_1$ , the nodes prefer CB/CT. Because CB/CT wastes overall energy compared to packet forwarding, the performance of the proposed scheme can be even worse than that of the pure packet-forwarding scheme. When  $\beta_2 > \beta_1$ , the nodes prefer packet forwarding, and the performance degrades gradually with the increase of the ratio. When  $\beta_2 = \beta_1$ , the performance improvement is maximized. This is because the nodes have no difference between CB/CT and packet forwarding for the cost function. (Notice that if the overhead for signalling is considered, the above claim may no longer be not valid.) When  $\beta_1$  is small, the performance improvement is also small.

This is because the costs of the energy-depleting nodes are not significantly higher than those of the energy-redundant nodes. As a result, the routing algorithms still select the energy-depleting nodes and the network lifetime is short. When  $\beta_1 = \beta_2$  and they are sufficiently large, the performance differences from  $\beta_1 = 1$  and  $\beta_1 = 10$  are trivial. When  $\beta_2$  is different from  $\beta_1$ , the performance degrades faster for larger  $\beta_1$ . This fact is because the values of the cost functions in (35) are very sensitive to the values of  $\beta_1$  and  $\beta_2$  when they are large.

## V. CONCLUSIONS

In this paper, we have studied the impact of CB/CT on the design of higher level routing protocols. Specifically, using CB/CT, we have proposed a new idea to bypass the energy-depleting nodes and communicate directly with sinks or faraway nodes, so as to improve the lifetimes of wireless sensor networks. First, we have developed a closed-form analysis of the effectiveness of CB/CT to enhance a wireless link. With this enhancement, the new routes can be constructed by CB/CT, so that the information flow can avoid the energy-depleting nodes. We have proposed static and dynamic routing algorithms. In addition, we have investigated the dynamic behavior of the proposed algorithms and studied the preferences between packet forwarding and CB/CT. From the analytical and simulation results, we have seen that the proposed algorithms can reduce the payloads of energy-depleting nodes by about 90% in a 2D disk case and increase lifetimes about 10% in general networks, compared with existing scheme techniques.

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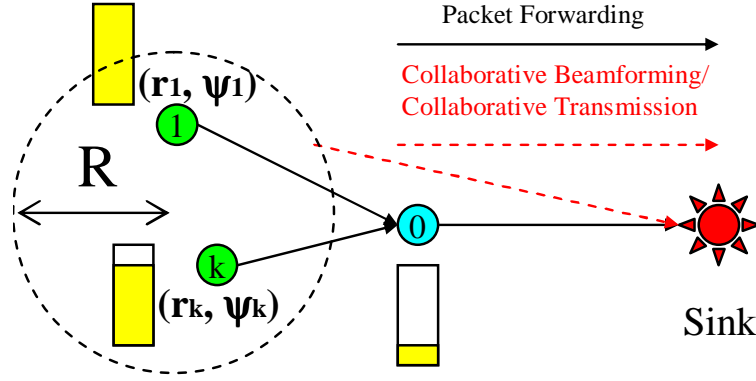


Fig. 1. System Model

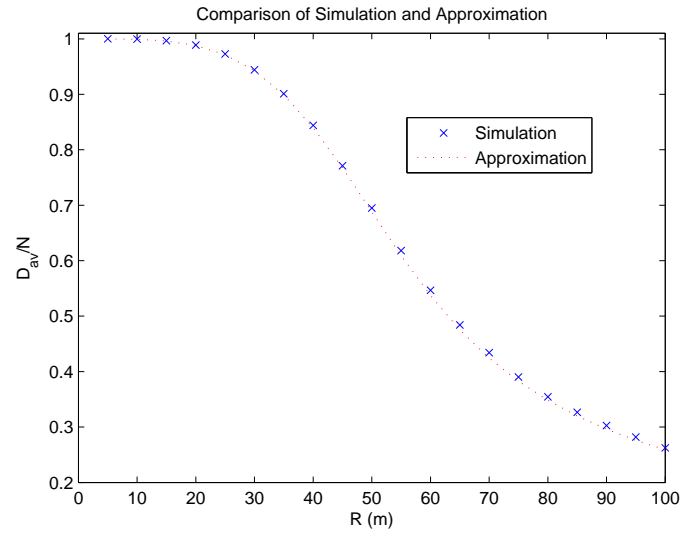


Fig. 2. Approximation of CT Effectiveness: Signal Enhancement vs. Radius

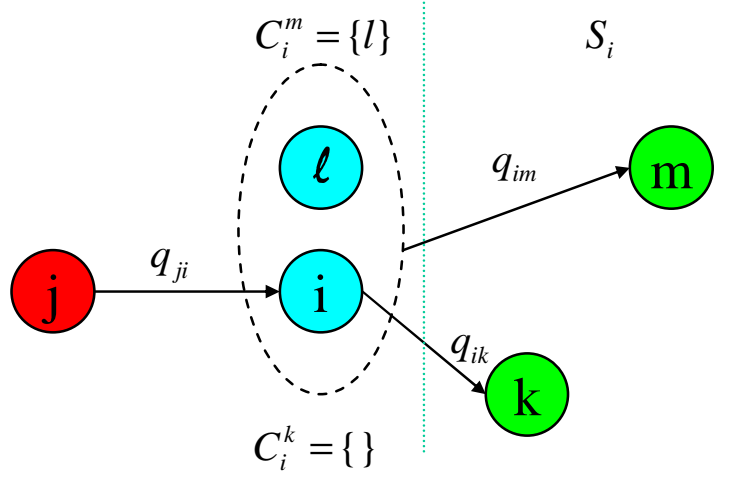


Fig. 3. CB/CT Routing Model

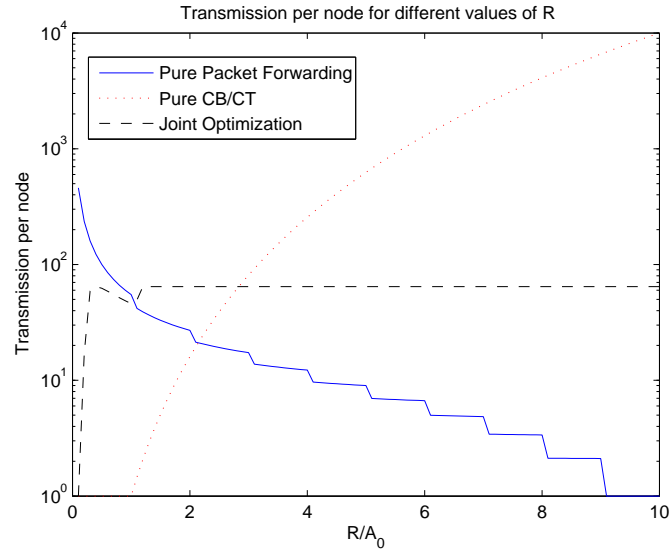


Fig. 4. Analytical Results for 2D Disk Case

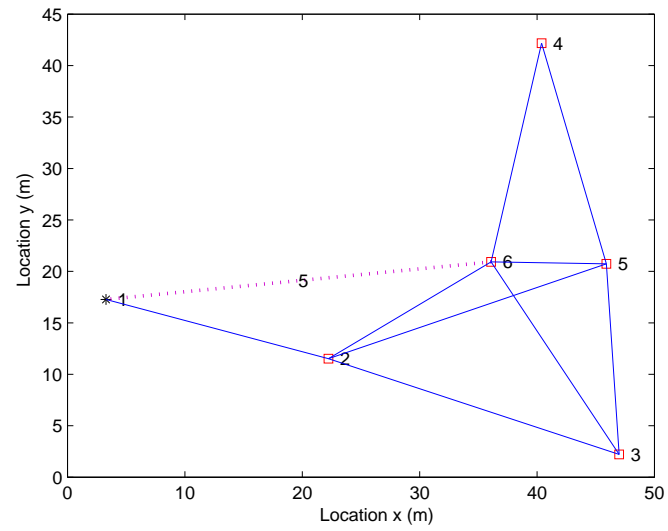


Fig. 5. Snapshot of CB/CT Routing

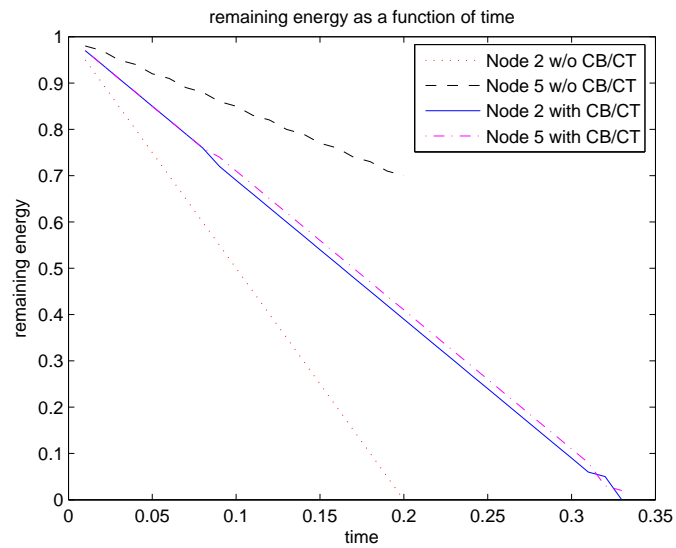


Fig. 6. Remaining Energy over Time with and without CB/CT

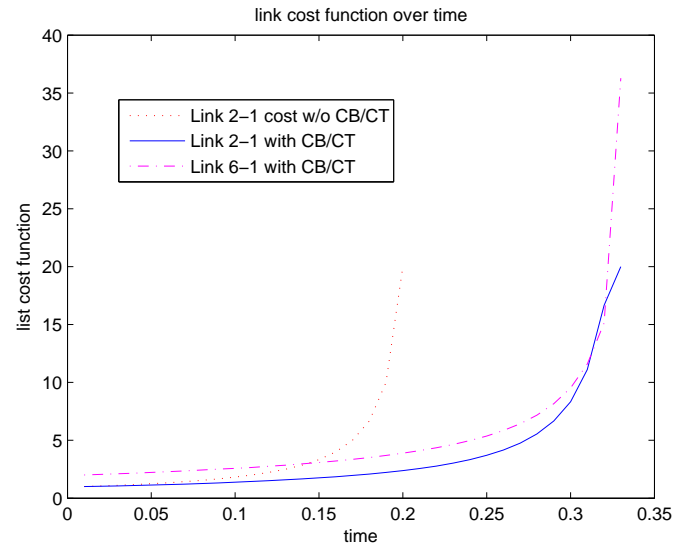


Fig. 7. Link Cost over Time with and w/o CB/CT

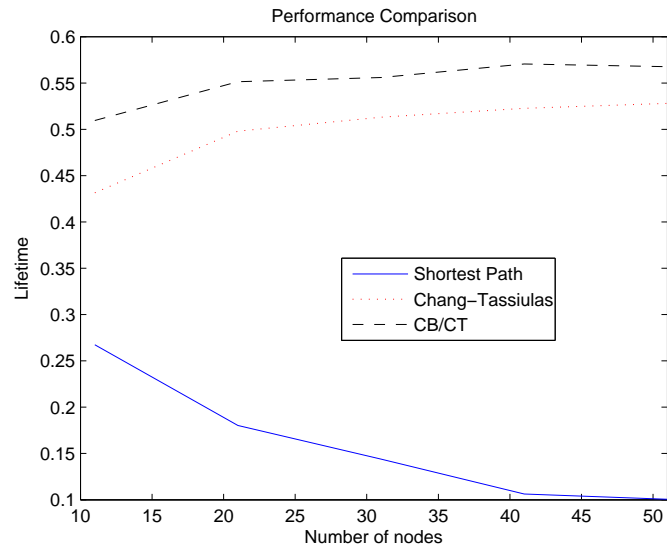


Fig. 8. Lifetime Improvement Comparison

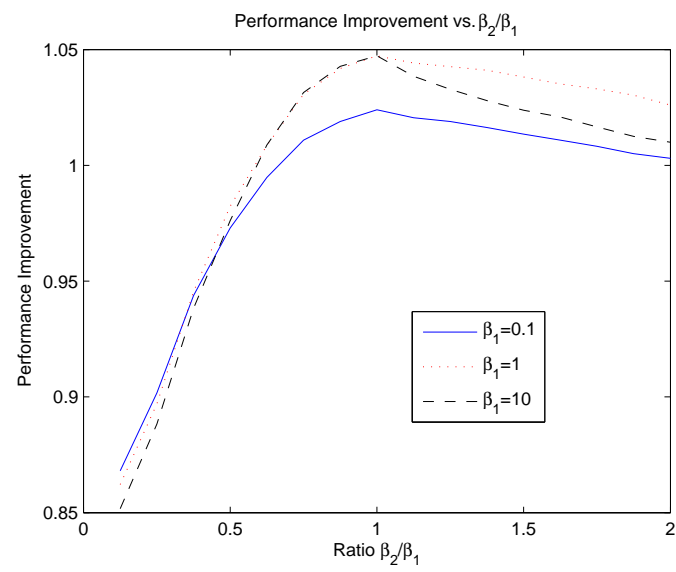


Fig. 9. Lifetime Improvement vs. Ratio  $\beta_2/\beta_1$